The Astrophysical Journal, 626:431–438, 2005 June 10

PRECISION RADIAL VELOCITIES OF DOUBLE-LINED SPECTROSCOPIC BINARIES WITH AN IODINE ABSORPTION CELL

Maciej Konacki
Department of Geological and Planetary Sciences, California Institute of Technology, MS 150-21,
1201 East California Boulevard, Pasadena, CA 91125; maciej@gps.caltech.edu
Received 2004 October 15; accepted 2005 February 25

ABSTRACT

A spectroscopic technique employing an iodine absorption cell (I_2) to superimpose a reference spectrum onto a stellar spectrum is currently the most widely adopted approach to obtain precision radial velocities of solar-type stars. It has been used to detect ~80 extrasolar planets out of ~130 known. Yet in its original version, it only allows us to measure precise radial velocities of single stars. In this paper, we present a novel method employing an I_2 absorption cell that enables us to accurately determine radial velocities of both components of double-lined binaries. Our preliminary results, based on the data from the Keck I telescope and HIRES spectrograph, demonstrate that 20–30 m s^{-1} radial velocity precision can be routinely obtained for "early" type binaries (F3–F8). For later type binaries, the precision reaches ~10 m s^{-1}. We discuss applications of the technique to stellar astronomy and searches for extrasolar planets in binary systems. In particular, we combine the interferometric data collected with the Palomar Testbed Interferometer with our preliminary precision velocities of the spectroscopic double-lined binary HD 4676 to demonstrate that with such a combination one can routinely obtain masses of the binary components accurate at least at the level of 1.0%.

Subject headings: binaries: spectroscopic — stars: fundamental parameters — stars: individual (HD 4676, HD 109358, HD 206901, HD 209458, HD 282975) — techniques: radial velocities

1. INTRODUCTION

The idea of passing starlight through an absorption medium to superimpose a set of reference lines and subsequently precisely measure radial velocities was first proposed by Griffin & Griffin (1973). At that time, Griffin & Griffin (1973) used the atmosphere and the telluric H_2O and O_2 lines. In order to overcome systematic errors in velocities caused by, among other things, the atmospheric pressure changes and hence shifts in the position of the telluric lines, Campbell & Walker (1979) introduced for the first time an absorption cell (containing a toxic hydrogen fluoride gas). This technique was subsequently used to carry out a pioneering precision radial velocity survey of 16 stars over a period of six years (1981–1987; Campbell et al. 1988). It is conceivable that Campbell et al. would have detected the first extrasolar planet if they had targeted a larger number of stars, as their average velocity precision was ~13 m s^{-1}.

Marcy & Butler (1992) took the absorption cell technique to a new level by introducing an iodine (I_2) absorption cell with the modeling of a spectrograph point spread function (PSF). The gaseous iodine, besides being much less toxic, has a strong line absorption coefficient (and hence requires a path length of only a few centimeters) and offers a dense forest of absorption lines over the wavelength range of 500–630 nm. In their approach, the Doppler shift of a star spectrum $\Delta\lambda$ is determined by solving the following equation (Marcy & Butler 1992):

$$I_{\rm obs}(\lambda) = [I_s(\lambda + \Delta\lambda_s) T_{\rm I_2}(\lambda + \Delta\lambda_{\rm I_2})] \otimes {\rm PSF}, \qquad (1)$$

where $\Delta\lambda_s$ is the shift of the star spectrum, $\Delta\lambda_{\rm I_2}$ is the shift of the iodine transmission function $T_{\rm I_2}$, $\otimes$ represents a convolution, and PSF represents a spectrograph PSF. The parameters $\Delta\lambda_s$ and $\Delta\lambda_{\rm I_2}$, as well as parameters describing the PSF, are determined by performing a least-squares fit to the observed (through the iodine cell) spectrum $I_{\rm obs}$. To this end, one also needs a high-S/N stellar spectrum I_s taken without the cell and used as a template for all the spectra observed through the cell and the I_2 transmission function $T_{\rm I_2}$ obtained with the Fourier Transform Spectrometer at the Kitt Peak National Observatory. The Doppler shift of a star spectrum is then given by $\Delta\lambda = \Delta\lambda_s - \Delta\lambda_{\rm I_2}$.

To date, the iodine technique has been successfully used to detect ~80 out of ~130 known extrasolar planets.[1] Most of these detections were accomplished by the California-Carnegie group (Marcy et al. 2003). The iodine technique—thanks to its conceptual simplicity—is the most commonly adopted way to obtain precision radial velocities. Iodine absorption cells are available on many spectrographs that are used for planet detections: HIRES at the 10 m Keck I (Keck Observatory), Hamilton at the 3 m Shane (Lick Observatory), UCLES at the 3.9 m Anglo-Australian Telescope (Anglo-Australian Observatory), HRS at the 9 m HET (McDonald Observatory), MIKE at the 6.5 m Magellan (Las Campanas Observatory), UVES at the 8 m Kueyen (Cerro Paranal), HDS at the 8.2 m Subaru (National Astronomical Observatory of Japan), and many others. Unfortunately, in its classical version the iodine technique can only be applied to single stars or spectroscopic binaries whose secondaries are so faint that their spectral lines are undetectable. This is dictated by the need to supply an observed template spectrum of each binary component for equation (1), but in the case of double-lined spectroscopic binaries it cannot be accomplished, since their spectra are obviously always composite and time variable.

In this paper, we present a novel technique that employs an I_2 absorption cell to obtain precision radial velocities of both components of double-lined spectroscopic binaries. The technique

[1] See the Extrasolar Planets Encyclopaedia at http://www.obspm.fr/encycl/encycl.html.

and its tests are described in § 2, and its applications to stellar astronomy and searches for planets in binary and multiple stellar systems are discussed in § 3.

2. THE METHOD

We can measure precise radial velocities of both components of a spectroscopic binary with an I_2 absorption cell in the following way. First, we always take two subsequent exposures of each (binary) target, one with and the other without the I_2 cell. This is contrary to the standard approach for single stars, in which an exposure without the cell (a template) is taken only once. This way we obtain an instantaneous template that is used to model only the adjacent exposure taken with the cell. Next, we perform the usual least-squares fit and obtain the parameters described in equation (1). Obviously, the derived Doppler shift, $\Delta\lambda_i$ (where i denotes the epoch of the observation), carries no meaning, since each time a different template is used (besides, it describes a Doppler "shift" of a composite spectrum that is typically different at each epoch). However, the parameters (in particular the wavelength solution and the parameters describing the PSF) are accurately determined and can be used to extract the star spectrum, $I^{*,i}_{\rm obs}(\lambda)$, for each epoch i by inverting equation (1),

$$I^{*,i}_{\rm obs}(\lambda) = \left[I^{i}_{\rm obs}(\lambda) \otimes^{-1} {\rm PSF}^{i}\right]/T_{\rm I_2}(\lambda), \qquad (2)$$

where $\otimes^{-1}$ denotes deconvolution (carried out using a modified Jansson technique; Gilliland et al. 1992) and PSF^i, symbolically, the set of parameters describing PSF at the epoch i. Such a star spectrum has an accurate wavelength solution and is free of the I_2 lines and the influence of a varying PSF. In the final step, the velocities of both components of a binary target can be measured with the well-known two-dimensional cross-correlation technique TODCOR (Zucker & Mazeh 1994) using as templates the synthetic spectra derived with the ATLAS9 and ATLAS12 programs (Kurucz 1995) and matched to the observed spectrum $I_s(\lambda)$ (Konacki et al. 2003b). The formal errors of the velocities can be derived from the scatter between the velocities from different echelle orders or using the formalism of TODCOR (Zucker & Mazeh 1994).

The above approach will produce radial velocities that may suffer from two possible sources of systematic errors: (1) the numerical procedure of extracting a star spectrum from an exposure taken with the I_2 cell could imaginably introduce systematic errors, and (2) TODCOR itself could also produce systematic errors. It has never been tested at a high velocity precision (for example, $\sim$10 m s^{-1}), and the use of synthetic spectra could be a source of systematic errors.

In order to demonstrate our method and investigate the systematic errors, we have observed a number of targets with the HIRES spectrograph at the Keck I telescope. HIRES equipped with an I_2 absorption cell has been successfully used to detect many extrasolar planets (Marcy et al. 2003). We have observed HD 209458 (a single star with a known short-period extrasolar planet, $V = 7.6$ mag), HD 109358 (a velocity standard, $V = 4.3$ mag), HD 4676 (a double-lined spectroscopic binary, $V = 5.0$ mag), HD 282975 (a double-lined spectroscopic binary in Pleiades, $V = 10.0$ mag), and HD 206901 (a triple system, $V = 4.2$ mag). The data span is approximately 2 yr for HD 209458 (from mid-2002 to mid-2004), 1 yr for HD 4676, HD 282975, and HD 206901 (from mid-2003 to mid-2004), and $\sim$10 minutes for HD 109358 (on 2004 March 29). With the exception of HD 209458, whose spectra had a typical S/N of 40–80 (HD 209458 was initially used as a standard star for a separate transiting planet search and was observed with moderate exposure times; see Konacki et al. 2003a, 2003b), the S/N of all other spectra was typically in the range of 150–300.

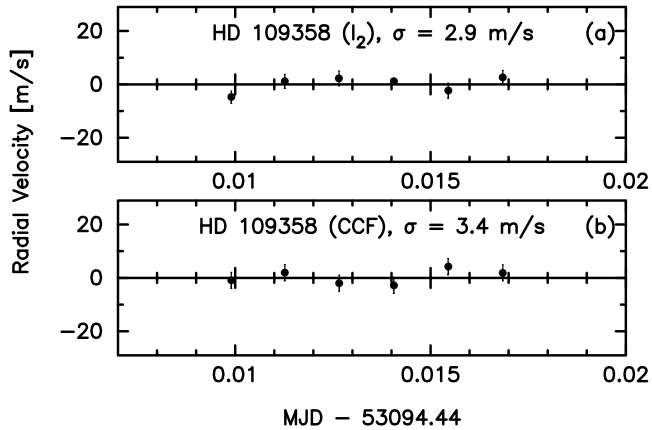

FIG. 1.—Radial velocities of HD 109358 computed with (*a*) the traditional iodine (I_2) technique and with (*b*) the proposed method.

Since in our approach we do not assume that an observed object must have a composite spectrum, the method can be applied to single stars as well. Obviously, there is no need to analyze the spectra of single stars in such a way, but the velocities computed in both ways (eqs. [1] and [2]) can be compared and used to explore possible additional errors originating in the proposed procedure. Two such comparisons are presented in Figures 1 and 2. Figure 1 shows six velocity measurements of HD 109358 over a period of about 10 minutes. HD 109358 is a high-precision radial velocity (RV) standard proposed by the Geneva group (Udry et al. 1999). Clearly, the two velocity sets have very similar scatter, and no additional errors at the 3 m s^{-1} can be seen. The second test (Fig. 2) concerns HD 209458 (the data span is 2 yr), a well-known star harboring a transiting giant planet with an orbital period of 3.52 days. Its orbital parameters are very accurately known (Naef et al. 2004) and hence were fixed in this test. The only parameter for which we fit was a velocity offset. The test does not reveal any additional errors, either. In fact, the velocities computed using a cross-correlation function (CCF) have a smaller rms (10 vs. 14 m s^{-1}) than the velocities computed with the traditional iodine approach, most likely because of a mediocre S/N of the spectra of HD 209458 (the iodine technique with PSF modeling works best on high-S/N spectra).

In order to test our method on a truly binary spectrum, we have observed HD 4676 (64 Psc), a nearby (23 pc) binary star composed of two F8 dwarfs. HD 4676 AB has an orbital period of 13.8 days and a brightness ratio of $\sim$0.9. Abt & Levy (1976) were the first to determine its spectroscopic orbit, which was later improved by Nadal et al. (1979) and Duquennoy & Mayor (1991). Moreover, its astrometric orbit is known from the Palomar Testbed Interferometer (PTI; Boden et al. 1999). This has important consequences for our work, as such astrometric data can be used to verify our precision radial velocities: orbital models for astrometric and spectroscopic measurements share most of the orbital parameters and can be used together to perform a combined least-squares fit (see, e.g., Konacki & Lane 2004).

We have observed HD 4676 over a period of one year on five occasions (2003 August 11, 2003 August 12, 2003 November 17, 2003 November 18, and 2004 July 18) and obtained 24 RV measurements for each component. The average formal RV error is 25 m s^{-1} for the primary and 28 m s^{-1} for the secondary. The quality of the data was verified by performing a combined fit to

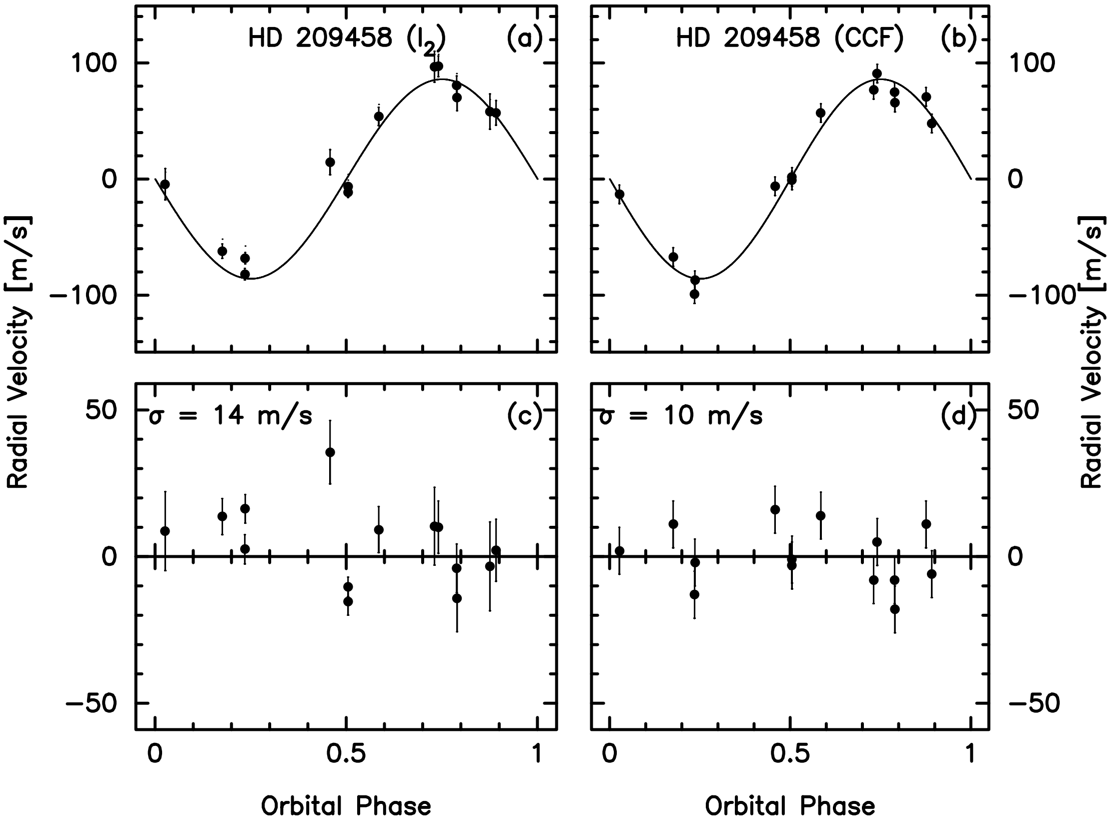

FIG. 2.—Radial velocities of HD 209458 computed with (*a*) the traditional iodine (I_2) technique and with (*b*) the proposed method. The data span is 2 yr. In (*c*) and (*d*) are shown the best-fit residuals as a function of phase.

our RVs and the astrometric data published by Boden et al. (1999). The details of the fit are presented in Figure 3. The postfit rms of 24 m s^{-1} is in very reasonable agreement with the formal RV errors and is 27 times smaller than the rms reported by Duquennoy & Mayor (1991). It obviously results in a much better determination of the orbital and physical parameters of the system. We discuss it in detail in § 3.1.

The most important remaining issue is whether TODCOR and the use of synthetic spectra could introduce any systematic errors to RVs. While errors that simply increase the postfit rms are not particularly troubling, one can in principle expect errors that may depend on the orbital phase and possibly affect the best-fit values of the orbital parameters. A common-sense way to detect such errors is to apply our method to simulated spectra of HD 4676 and try to recover the RVs assumed in the simulation. We have performed such tests and have not detected any systematic errors. There is, however, an even better way to control these errors. As already mentioned, thanks to high-precision astrometry of HD 4676 from PTI (Boden et al. 1999), one can perform a combined fit to the astrometric and spectroscopic data. If there existed any significant phase-dependent systematic variations of the velocities, they would be detectable in the postfit residuals from the combined solution. Clearly, these are absent in our solution (Fig. 3), and χ^2/dof is 1.18.

It should be noted that the best-fit rms of 24 m s^{-1} for the RVs of the primary and secondary is clearly larger than one would expect if the RV errors were photon-limited (2–3 m s^{-1}; Butler et al. 1996). Possible sources of additional errors include a mismatch between the synthetic templates and observed spectra and astrophysical phenomena (e.g., starspots, convective inhomogeneities; see Saar et al. 1998). We do not yet have enough data for other binaries to fully address this issue. Nevertheless, it is reasonable to expect that for later type stars (with more spectral lines), the velocity precision will be higher. This appears to be confirmed by our velocities of HD 282975, a double-lined spectroscopic binary from Pleiades ($P_{\rm orb} = 26$ days), which is composed of two G6 dwarfs. The postfit rms is 11 m s^{-1} for the primary and 13 m s^{-1} for the secondary and is ~80 times smaller than the rms reported by Mermilliod et al. (1992). The best fit is based on only eight RVs, but from our experience with HD 4676 we know that early accuracy is later confirmed by a larger data set.

Finally, let us note that the iodine technique for single stars typically produces RVs that have an arbitrary offset (unless special steps are undertaken; see Nidever et al. 2002). In our approach, which employs synthetic spectra, one can in principle calibrate and refer the velocities to a standard system of stars. We plan to do this once we collect enough observations of the RV standards.

3. APPLICATIONS

3.1. *Stellar Astronomy*

Modern tests of stellar structure and evolution models require stellar masses accurate to 2% or better (Andersen 1991). Stellar masses are traditionally derived from the observations of binary stars by combining (1) photometric (light curves) and spectroscopic (RVs) data for double-lined eclipsing binaries, (2) relative astrometry and spectroscopic data for double-lined binaries, (3) data from spectroscopy, relative astrometry, and parallax for single-lined binaries, and (4) absolute astrometry. There are currently known about 60 binaries with masses of the components accurate at the level of 2% or better (see, e.g., Lastennet & Valls-Gabaud 2002). Almost all of them are eclipsing binaries, and

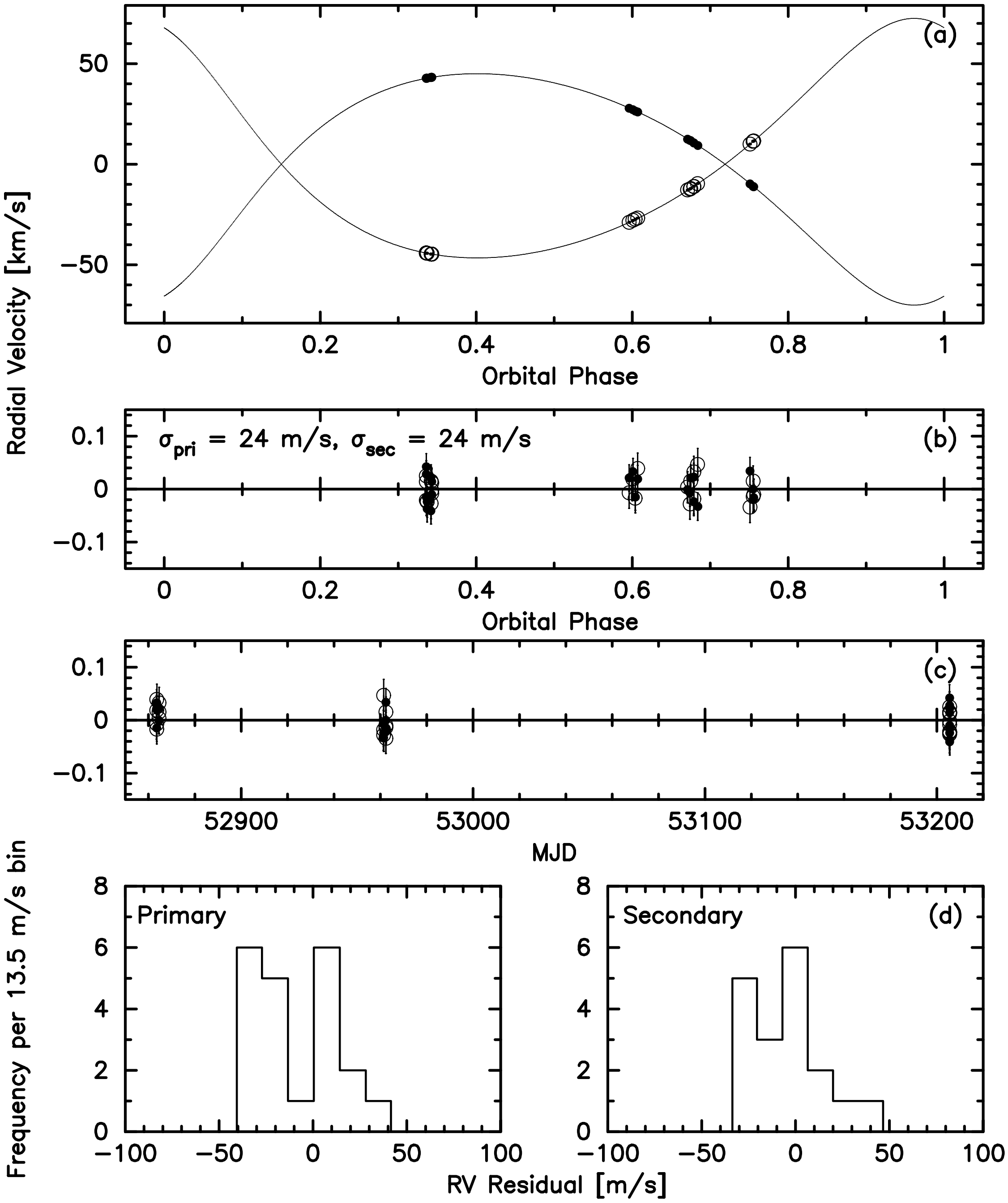

FIG. 3.—(*a*) Observed (*filled circles*: primary; *open circles*: secondary) and modeled (*solid lines*) radial velocities of HD 4676. In (*b*) and (*c*) are shown the best-fit residuals as a function of phase and time. (*d*) Histogram of the residuals.

most of them have components with masses in the 1–3 $M_\odot$ range (more massive and hence larger stars are more likely to be eclipsing, for a given orbital period).

Optical interferometry offers the unique opportunity to determine visual orbits of double-lined spectroscopic binaries (apparent semimajor axes at the milliarcsecond level; for a recent discussion, see Konacki & Lane 2004) and subsequently masses of the components, regardless of their size. Up to date, about 20 spectroscopic binaries have had their orbits determined with optical interferometers (Quirrenbach 2001). In a few cases, when combined with RV measurements, they already produced component masses accurate at the level of 1%–2%.

Our RVs constitute an excellent complement to precise astrometric orbits from optical interferometers. This is demonstrated well by HD 4676. Boden et al. (1999) combined their interferometric data of HD 4676 from PTI with the RV measurements of Duquennoy & Mayor (1991). They have determined the masses to be $M_1 = 1.223 \pm 0.021\ M_\odot$ (1.7%) and $M_2 = 1.170 \pm 0.018\ M_\odot$ (1.5%), the velocity amplitudes to be $K_1 = 57.35 \pm 0.31$ km s^{-1} and $K_2 = 59.95 \pm 0.32$ k ms^{-1}, and the inclination to be $i = 73\overset{\circ}{.}80 \pm 0\overset{\circ}{.}92$. The relative error in the masses ($\Delta M/M$) is dominated by the error in the orbital inclination, $3\Delta i \cos(i)/\sin(i) \approx 1.4\%$, but the errors in the velocity amplitudes also contribute. In order to make the best out of PTI data, we used our RVs and performed a new combined fit. The best-fit orbital and physical parameters of the system are presented in Tables 1 and 2. The relative error in the masses is now 1.2%, and the overall quality of the fit has improved. In this

TABLE 1
Best-fit Orbital Parameters for HD 4676

Parameter	Value
Apparent semimajor axis, $\hat{a}$ (mas)	6.545 ± 0.0133
Period, P (days)	$13.8244906 \pm 4.3 \times 10^{-5}$
Time of periastron, T_p (MJD)	50905.9746 ± 0.0067
Eccentricity, e	0.23657 ± 0.00063
Longitude of periastron, ω (deg)	203.057 ± 0.073
Longitude of ascending node, Ω (deg)	207.41 ± 0.65
Inclination, i (deg)	73.92 ± 0.80
Assumed K-band magnitude difference, ΔK	0.11
Velocity amplitude of primary, K_1 (km s^{-1})	57.552 ± 0.037
Velocity amplitude of secondary, K_2 (km s^{-1})	59.557 ± 0.038
Reduced χ^2, χ^2/dof	1.18

specific case, the ultimate accuracy of the masses is still limited by the accuracy of the orbital inclination. However, since the radial velocities are so precise, one can simply take more astrometric data with PTI and improve the mass determinations even more. Clearly, our approach will be of great use for all those binaries that have orbital inclinations closer to an edge-on configuration. In particular, light curves of eclipsing binaries combined with precise RVs should produce mass determinations accurate at the 0.1% level on a regular basis.

Precise RVs can obviously be used to determine not only the masses of the companions but the distance to the binary as well. For example, the parallax of HD 4676 is formally very accurate, 43.496 ± 0.089 mas (distance of 22.991 ± 0.047 pc; the final accuracy will depend on how well the brightness ratio of the binary components is known). In this context, HD 282975 (Fig. 4) appears as a particularly interesting binary, as it can be used to derive a very precise distance to Pleiades. To this end, one needs interferometric astrometry of HD 282975, which should be easy to obtain with the Keck Interferometer (HD 282975 is too faint for PTI). Finally, precise RVs can be used to explore the regime of circular or almost circular orbits (the error of the eccentricity of HD 4676 is only 6.0×10^{-4}; Table 1) and the cutoff period below which orbits are circularized.

3.2. *Extrasolar Planets in Binary Stellar Systems*

Duquennoy & Mayor (1991) have demonstrated that the frequency of binaries (BF) among field stars older than 1 Gyr is 57%. The studies of multiplicity of pre–main-sequence (PMS) stars in the Taurus and Ophiuchus star-forming regions show that the BF for systems in the separation range 1–150 AU is twice as large as that of the older field stars (Simon et al. 1995). Further investigations have concluded that the BF is lower for young stellar clusters (and similar to the BF of the field stars) and that the binary frequency for PMS stars seems to be anticorrelated with the stellar density (Mathieu et al. 2000). Nonetheless, the BF is very high for both field and PMS stars, and one can argue that it may not be possible to assess the overall frequency and properties of extrasolar planets without addressing binary (and multiple) stellar systems.

Supporting arguments come from the presence of circumstellar and circumbinary disks around binaries. One of the prime examples of the circumstellar disks in a binary system is the case of L1551 IRS 5. Rodríguez et al. (1998) show that L1551 IRS 5 is a binary PMS star with a separation of 45 AU in which each component is surrounded by a disk. The radii of the disks are 10 AU, and the estimated masses are 0.06 and 0.03 $M_\odot$, supposedly enough to produce planets. Recently, McCabe et al. (2003) spatially resolved mid-infrared scattered light from the protoplanetary disk around the secondary of the PMS binary HK Tau AB. The inferred sizes of the dust grains are in the range 1.5–3 μm, which suggests that the first step in planet formation, dust grain growth, has occurred in this disk. Millimeter and submillimeter measurements of the dust continuum emission enable us to measure the total masses of the disks. These observations show that the circumbinary disks may be reduced in size and mass but still are present even in close systems. The circumbinary disks are observed at millimeter wavelengths around many PMS spectroscopic binaries. Such massive disks are, however, rare around wide binaries with separations of 1–100 AU. This is confirmed by numerical works that predict circumstellar and circumbinary disks truncated by the companions (Lubow & Artymowicz 2000). The circumstellar disks have outer radii 0.2–0.5 times the binary separation, while the circumbinary disks have inner radii 2–3 times the semimajor axis of the binary. Finally, the measurements of the infrared excess emission show no difference in frequency of the excess among binaries and single stars. It indicates that the circumstellar material in binary systems may be similar in temperature and surface density to that in the disks surrounding single stars (Mathieu et al. 2000).

The problem of stability of the planetary orbits in binaries was recognized a long time ago. It was mostly approached with the numerical studies of the elliptic restricted three-body problem. The orbital configurations considered include the so-called P-type (planet-type, circumbinary orbits), S-type (satellite-type, circumprimary or circumsecondary orbits), and L-type orbits (liberator-type, orbits around stable Lagrangian points L4 or L5 for the mass ratios $\mu < 0.04$). There are many papers concerning the stability of S-type motions (e.g., Benest 2003; Pilat-Lohinger & Dvorak 2002; Rabl & Dvorak 1988). They aimed at developing empirical stability criteria in the framework of the circular three-body problem (see, e.g., Graziani & Black 1981; Black 1982; Pendleton & Black 1983), the stability of periodic orbits, and the stability of the test particles in binary systems as a function of the eccentricity of the binary. The P-type motions were also investigated (Pilat-Lohinger et al. 2003; Broucke 2001; Holman & Wiegert 1999), as were the L-type orbits (see, e.g., Laughlin & Chambers 2002). Unfortunately, most of the analytical papers deal only with circular binary orbits, numerical studies are confined to special mass ratios, and the integration

TABLE 2
Physical Parameters for HD 4676

Parameter	Primary	Secondary
Semimajor axis, $a_{1,2}$ (AU)	$0.073953 \pm 4.8 \times 10^{-5}$	$0.076529 \pm 5.0 \times 10^{-5}$
Mass, M ($M_\odot$)	1.210 ± 0.014	1.169 ± 0.014
Parallax, κ (mas)	43.496 ± 0.089	43.496 ± 0.089
Distance, d (pc)	22.991 ± 0.047	22.991 ± 0.047
Spectral type	F8 V	F8 V

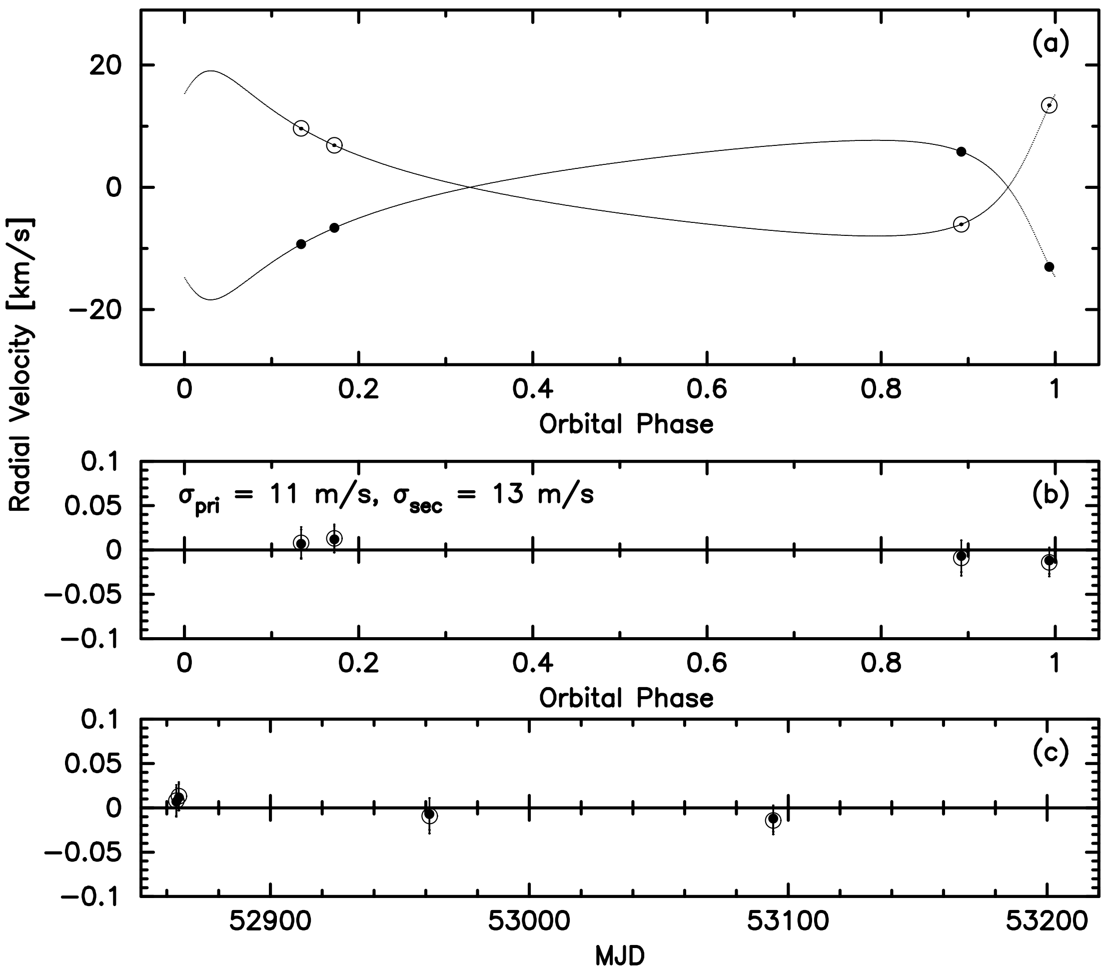

FIG. 4.—(*a*) Observed (*filled circles*: primary; *open circles*: secondary) and modeled (*solid lines*) radial velocities of HD 282975. In (*b*) and (*c*) are shown the best-fit residuals as a function of phase and time.

times used are relatively short. In addition, they are almost exclusively restricted to the framework of the three-body problem. Some of these issues are addressed by Holman & Wiegert (1999), who studied a range of mass ratios and eccentricities and used long integration times (at least 10^4 periods of the binary). Nonetheless, we can safely conclude that planets in binary stellar systems, once formed, would enjoy a wide range of stable orbits.

However, the theories of planet formation in binary stellar systems are still at early stages. Whitmire et al. (1998) studied terrestrial planet growth in the circumprimary habitable zones in a binary system. They considered a four-body system of two stars and two planetesimals, for which by varying the orbital parameters of the binary (the semimajor axis, eccentricity, and mass ratio) they were able to determine a critical semimajor axis of the binary below which the secondary does not allow a growth of the planetesimals (planetesimals are accelerated by the secondary, their relative velocity is larger than the critical value, and their collisions become destructive). Based on this criterion, they concluded that about 60% of nearby solar-type binaries cannot be excluded from having a habitable planet. Marzari & Scholl (2000) analyzed α Cen AB (semimajor axis of 23 AU, eccentricity of 0.52, mass ratio 1.1/0.92), a prototype close binary system, and demonstrated that the planetesimals can accrete into planetary embryos. Barbieri et al. (2002) continued the study and showed that planetary embryos can grow into terrestrial planets in about 50 Myr. Somewhat contrary to this result, Nelson (2000), who analyzed a binary system similar to L1551 IRS 5, found that planet formation is unlikely in equal-mass binary systems with separation of about 50 AU. Yet another result by Boss (1998) claims that a stellar companion can induce a multi–Jupiter-mass planet formation. Clearly, there is a lack of consensus, and the planet formation theories would certainly benefit from observational constraints.

Unfortunately, current RV searches for extrasolar planets have been limited to single stars or binaries with large apparent separations. Despite that prejudice, out of ~130 extrasolar planets, 18 belong to stars that also have stellar companions (Eggenberger et al. 2004). They even seem to posses characteristics different from those of planets orbiting single stars. As recently pointed out by Eggenberger et al. (2004), (1) the most massive short-period planets orbit stars from multiple stellar systems, and (2) all these planets ($P_{\rm orb}$ < 40 days) tend to have very low eccentricities. It is a surprisingly interesting result, given that current RV surveys suffer from a selection effect: the binary stars with separations smaller than ~2″ have been excluded from the surveys. The exception here is HD 41004 AB, which has a separation of 0″.5. Presumably, this star entered the Geneva RV program as a single star and was later found to be a triple system in which the primary has apparently a giant planet (Eggenberger et al. 2004) and the secondary and tertiary are very faint (an M star and a putative brown dwarf). Thus, these stars from binary or multiple stellar systems that we know harbor planets have a distant or/and faint stellar companion. There is a need to perform an unbiased survey for extrasolar planets and substellar companions to stars from

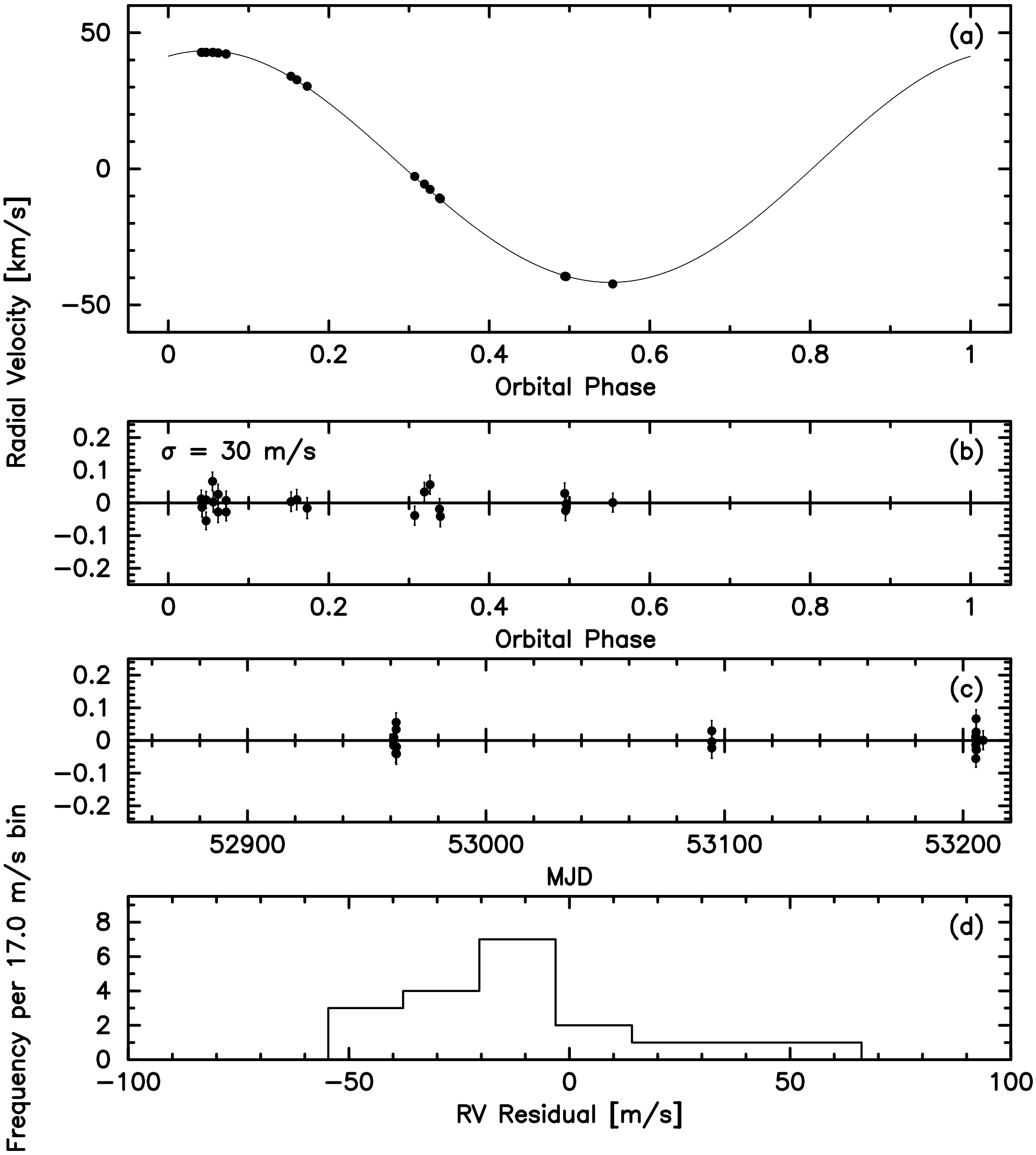

FIG. 5.—(*a*) Observed (*filled circles*) and modeled (*solid line*) radial velocities of HD 206901 B. In (*b*) and (*c*) are shown the best-fit residuals as a function of phase and time. (*d*) Histogram of the residuals.

multiple systems that will probe different physical separations and brightness ratios.

To this end, two years ago we initiated a survey to detect planets in binary stellar systems with the Keck I and HET telescopes. Our survey covers about ~450 binary stars from the northern and southern hemispheres. Preliminary results for one of our representative targets, κ Peg, are shown in Figure 5. Also designated HR 8315, HD 206901, and HIP 107354, κ Peg is a known triple system of which the spectral lines of the two brightest components AB (apparent semimajor axis 0."4) can be easily identified ($\Delta m = 0.04$, $P_{\rm orb} = 11.59$ yr), and the component B is itself a single-lined spectroscopic binary with an orbital period of ~5.97 days (e.g., Mayor & Mazeh 1987). The radial velocities of the primary do not reveal any interesting variations and are of inferior quality because of a large $v \sin i \approx 30$ km s^{-1}. On the other hand, the RVs of the sharp-lined secondary are more than acceptable (given an early spectral type of the star, F3I V) with an rms of ~30 m s^{-1}. It is an improvement of 30 times in the rms compared to the work of Mayor & Mazeh (1987) and demonstrates the usefulness of our approach. Since the iodine cells are available on many high-resolution spectrographs, our method clearly opens exciting opportunities in the studies of other multiple systems.

4. SUMMARY

We have introduced a new method to measure precision radial velocities of double-lined spectroscopic binaries with an iodine absorption cell. Our initial data sets demonstrate 20–30 m s^{-1} velocity precision for "early" (F3–F8) type and ~10 m s^{-1} for later type binaries. If combined with interferometric astrometry, such velocities enable us to determine the masses of the components of binary stars accurate at least at the level of 1%. Our method also makes it possible to perform a search for extrasolar planets in binary and multiple stellar systems where the brightness of the primary and the secondary is comparable. This allows us to probe a regime of the parameter space of the formation and evolution of extrasolar planets not covered by other surveys.

M. K. would like to thank Shri Kulkarni for very generous support and guidance; Guillermo Torres and Dimitar Sasselov for many discussions on stellar spectroscopy; Eliza Miller-Ricci and Dimitar Sasselov for their high-resolution grid of synthetic stellar spectra; Krzystof Gozdziewski for a discussion on the stability of planets in binary systems; and the referee and Matthew Muterspaugh for careful reading of the manuscript and many useful suggestions. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. This work was supported by NASA through grant NNG04GM62G.

REFERENCES

Abt, H. A., & Levy, S. G. 1976, ApJS, 30, 273
Andersen, J. 1991, A&A Rev., 3, 91
Barbieri, M., Marzari, F., & Scholl, H. 2002, A&A, 396, 219
Benest, D. 2003, A&A, 400, 1103
Black, D. C. 1982, AJ, 87, 1333
Boden, A. F., et al. 1999, ApJ, 527, 360
Boss, A. P. 1998, BAAS, 30, 1057
Broucke, R. A. 2001, Celest. Mech. Dyn. Astron., 81, 321
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Campbell, B., & Walker, G. A. H. 1979, PASP, 91, 540
Campbell, B., Walker, G. A. H., & Yang, S. 1988, ApJ, 331, 902
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggenberger, A., Udry, S., & Mayor, M. 2004, A&A, 417, 353
Gilliland, R. L., Morris, S. L., Weymann, R. J., Ebbets, D. C., & Lindler, D. J. 1992, PASP, 104, 367
Graziani, F., & Black, D. C. 1981, ApJ, 251, 337
Griffin, R., & Griffin, R. 1973, MNRAS, 162, 243
Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621
Konacki, M., & Lane, B. F. 2004, ApJ, 610, 443
Konacki, M., Torres, G., Jha, S., & Sasselov, D. D. 2003a, Nature, 421, 507
Konacki, M., Torres, G., Sasselov, D. D., & Jha, S. 2003b, ApJ, 597, 1076
Kurucz, R. L. 1995, in ASP Conf. Ser. 78, Astrophysical Applications of Powerful New Databases, ed. S. J. Adelman & W. L. Wiese (San Francisco: ASP), 205
Lastennet, E., & Valls-Gabaud, D. 2002, A&A, 396, 551
Laughlin, G., & Chambers, J. E. 2002, AJ, 124, 592
Lubow, S. H., & Artymowicz, P. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 731
Marcy, G. W., & Butler, R. P. 1992, PASP, 104, 270
Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2003, in ASP Conf. Ser. 294, Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming & S. Seager (San Francisco: ASP) 1
Marzari, F., & Scholl, H. 2000, ApJ, 543, 328
Mathieu, R. D., Ghez, A. M., Jensen, E. L. N., & Simon, M. 2000, Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 703
Mayor, M., & Mazeh, T. 1987, A&A, 171, 157
McCabe, C., Duchêne, G., & Ghez, A. M. 2003, ApJ, 588, L113
Mermilliod, J.-C., Rosvick, J. M., Duquennoy, A., & Mayor, M. 1992, A&A, 265, 513
Nadal, R., Ginestet, N., Carquillat, J.-M., & Pedoussaut, A. 1979, A&AS, 35, 203
Naef, D., Mayor, M., Beuzit, J. L., Perrier, C., Queloz, D., Sivan, J. P., & Udry, S. 2004, A&A, 414, 351
Nelson, A. F. 2000, ApJ, 537, L65
Nidever, D. L., Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2002, ApJS, 141, 503
Pendleton, Y. J., & Black, D. C. 1983, AJ, 88, 1415
Pilat-Lohinger, E., & Dvorak, R. 2002, Celest. Mech. Dyn. Astron., 82, 143
Pilat-Lohinger, E., Funk, B., & Dvorak, R. 2003, A&A, 400, 1085
Quirrenbach, A. 2001, ARA&A, 39, 353
Rabl, G., & Dvorak, R. 1988, A&A, 191, 385
Rodríguez, L. F., et al. 1998, Nature, 395, 355
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 498, L153
Simon, M., et al. 1995, ApJ, 443, 625
Udry, S., Mayor, M., & Queloz, D. 1999, in IAU Colloq. 170, Precise Stellar Radial Velocities, ed. J. B. Hearnshaw & C. D. Scarfe (ASP Conf. Ser. 185; San Francisco: ASP), 367
Whitmire, D. P., Matese, J. J., Criswell, L., & Mikkola, S. 1998, Icarus, 132, 196
Zucker, S., & Mazeh, T. 1994, ApJ, 420, 806